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# Surface damage growth mitigation on KDP/DKDP optics using single-crystal diamond micro-machining

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## ABSTRACT

A process whereby laser-initiated surface damage on KDP/DKDP optics is removed by spot micro-machining using a high-speed drill and a single-crystal diamond bit, is shown to mitigate damage growth for subsequent laser shots. Our tests show that machined dimples on both surfaces of an AR coated doubler (KDP) crystal are stable, for 526nm, ~3.2ns pulses at ~12J/cm<sup>2</sup> fluences. Other tests also confirmed that the machined dimples on both surfaces of an AR coated tripler (DKDP) crystal are stable, for 351nm, ~3ns pulses at ~8J/cm<sup>2</sup>. We have demonstrated successful mitigation of laser-initiated surface damage sites as large as 0.14mm diameter on DKDP, for up to 1000 shots at 351nm, 13J/cm<sup>2</sup>, ~11ns pulse length, and up to 10 shots at 351nm, 8J/cm<sup>2</sup>, 3ns. Details of the method are presented, including estimates for the heat generated during micro-machining and a plan to implement this method to treat pre-initiated or retrieved-from-service, large-scale optics for use in high-peak-power laser applications.

**Keywords:** KDP, DKDP, laser damage, surface damage, mitigation, micro-machining

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## 1. INTRODUCTION

Surface damage that is initiated on machine finished KDP/DKDP surfaces during high-peak-power irradiation encompasses only a fraction of the clear aperture area. However, studies have shown that the damage can grow with the number of shots at laser fluences above ~5J/cm<sup>2</sup> [1,2]. A substantial increase in the useful lifetime of crystal optics can be achieved by stopping damage growth, thus mitigating obscuration caused by growing damage. Ideally this can be accomplished by eliminating the damage sites while they are small and returning the surface to its undamaged state. In previous work we explored several methods to mitigate the growth of laser-induced damage on KDP/DKDP crystals [3]. The methods investigated were CO<sub>2</sub> laser annealing, etching using aqueous solutions, femto-second laser ablation, and micro-machining. We found that the micro-machining method was the most promising method. Other studies at this Laboratory have focused on elucidating the mechanisms for initiation [4] and growth [5] of surface damage on optics, whereas the purpose of this effort is to validate the micro-machining method to successfully terminate damage growth on crystal optics.

Results of previous experiments showed that micro-machining, using a small, high speed motor and a single-crystal diamond bit that completely removes the damage pit, consistently halts the growth of surface damage on crystals[3]. This method was used to process surface damage sites on small-scale crystal optics to establish feasibility for processing large-scale optics. In this paper, we describe the method and we give the results of tests to validate it for damage growth mitigation. We also include estimates for the heat generated during the process and a concept to implement this method on large-scale optics for use in high-peak-power laser applications.

## 2. METHODOLOGY

## 2.1 Micro-machining set-up

Spot micro-machining is done using a small, high-speed motor with a single-crystal diamond bit, which are shown in Fig.1. The motor is a model I 51700 Pencil Grinder, manufactured by Dynabrade, Inc., Clarence, NY; it is an air-turbine motor that rotates at 65,000 RPM when 90 psi pressure is used. The single-crystal diamond tool was prepared according to custom specifications, by Chardon Tool Company, Chardon, OH. A schematic of the set-up for micro-machining is shown in Fig. 2 and Fig. 3 is a photograph of the apparatus. The motor is mounted on a micro-positioning stage that is attached to a rigid table. The positioning stage is controlled by a linear voltage drive transducer (LVDT) in a jog mode, with a maximum resolution of  $\sim 1$  micrometer per step. The rigid table is mounted directly adjacent to an X-Y positioning stage that holds the crystal optic in a vertical orientation. This orientation is preferred because it allows easy access to the surface for debris removal using a high velocity air-flow with a vacuum pick-up assist. A microscope with an attached COHU camera, is mounted opposite the machine tool. The microscope is focused through the crystal at the working surface of the optic, which provides a view of the damage site and the tip of the diamond tool. The working surface is illuminated at a glancing angle with a variable intensity light source.

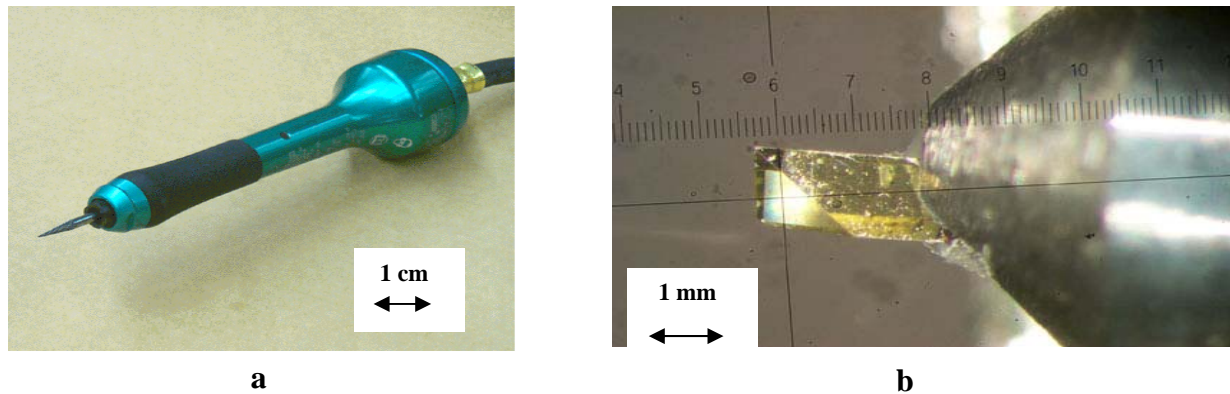


Figure 1. Spot micro-machining is done using a.) a high-speed air-turbine motor that turns 65,000 RPM , and b.) a single-crystal diamond end mill with a conical cutting edge.

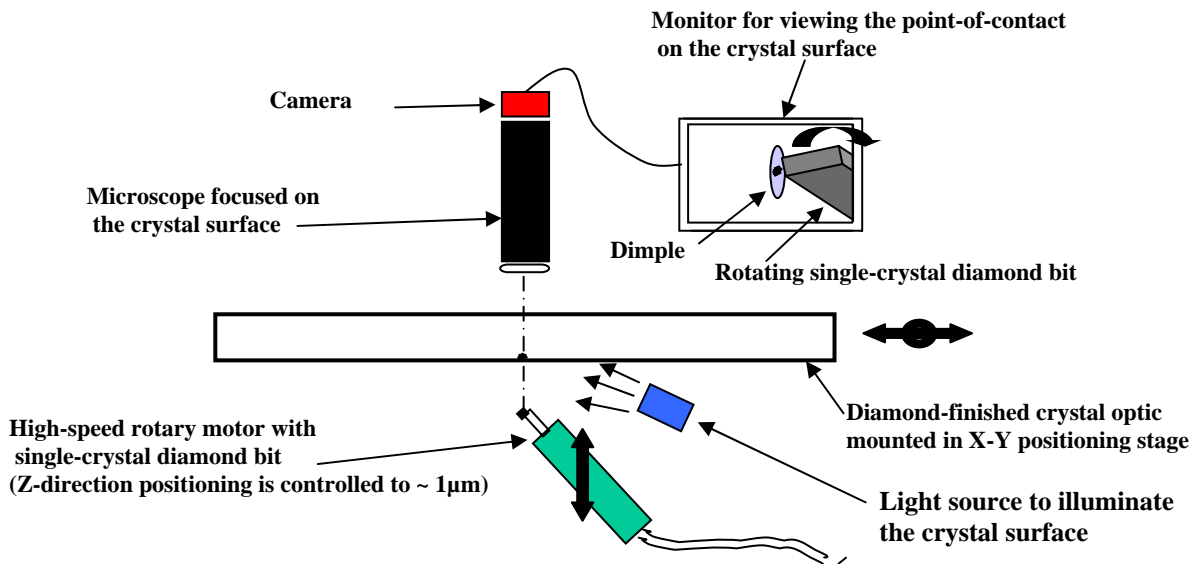


Figure 2. Schematic of the set-up for micro-machining damage sites on crystal surfaces.

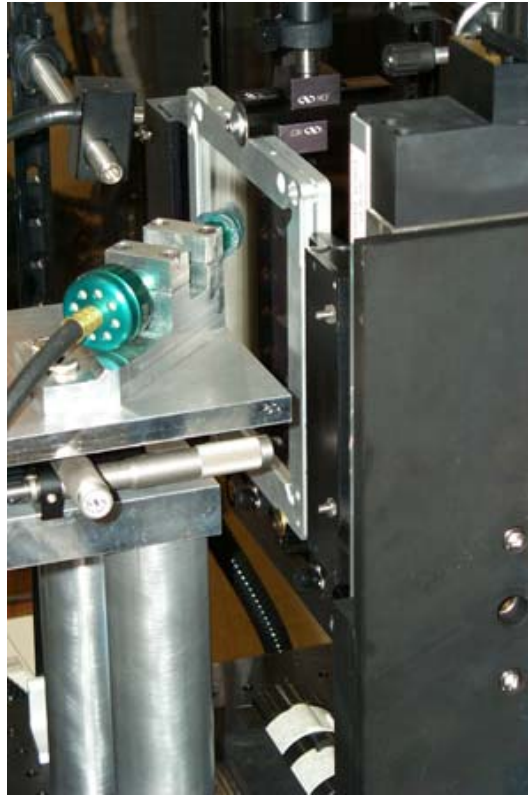


Figure 3. Photo of the set-up for micro-machining damage sites on crystal surfaces.

## 2.2 Micro-machining procedure

The procedure to micro-machine at a spot location on the optic surface is as follows: The optic is moved into the working position using the controller for the X-Y stage, and the microscope is focused at the working surface. The tool is slowly moved so that the spinning tip is within a few millimeters of the working surface as viewed using the microscope, camera, and video monitor. The jog controller for the tool stage is then used to move the tip toward the surface in incrementally smaller steps per jog until contact is made during  $\sim 1$  micrometer per jog step. The depth of the machine cut into the crystal is determined by counting the number of jog-steps after the initial contact with the surface. This same procedure is used to excavate an existing surface damage site; the nature of the scattered light from the damage site changes from multi-directional to directional, which is useful to determine that the cutting depth is sufficient to remove the damage.

A typical dimple that the tool makes on the surface is shown in Fig.4. The elongated, banana-shaped cut has a length-to-width-to-depth ratio of 30 : 6 : 1. The minimum length cut that was achieved with the diamond bit is about 55 micrometers, and the maximum length is about 1.1 millimeters.

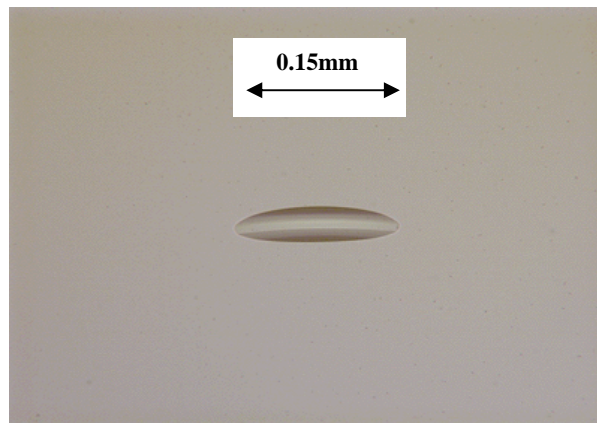


Figure 4. A typical dimple on the crystal surface, produced by micro-machining using a single-crystal diamond end mill bit. The dimple is smooth and crack-free. The size of the dimple is determined by the penetration depth during the cut. The ratios of the cut dimensions are: length/width/depth = 30/6/1

### 3. DATA

#### 3.1 Experiments to test dimple stability and mitigation

Initial experiments were done with both KDP and DKDP crystals to test the stability of the dimples that are micro-machined on un-damaged crystal surfaces. These tests were done to verify that the dimples themselves do not damage when illuminated with intense laser pulses. The test samples are 15 cm x 15 cm x 1 cm diamond-finished crystals that are either un-coated or with anti-reflection (AR) coatings on each surface. An array of different size dimples was machined on the surfaces of each crystal. The dimples in the array were spaced a few millimeters apart so that multiple sites are simultaneously illuminated by the test laser beam. The laser used for these tests is a Nd-YAG laser capable of operation at 527nm (doubled), ~3.2ns, or at 351nm (tripled), ~3ns. The diameter of the doubled beam is ~12mm and the fluence range is ~1 – 14J/cm<sup>2</sup>; the diameter of the tripled beam is ~30mm and the fluence range is ~1 – 10J/cm<sup>2</sup>. The tests are performed with the sample under vacuum at ~2.5torr.

Additional tests were done to validate the micro-machining method for mitigating the growth of surface damage. The test sample was a 15 cm x 15 cm x 1cm, AR coated, diamond-finished DKDP crystal that contained a variety of surface damage sites which were initiated during previous laser testing at 351nm, ~3ns pulse length. A total of 24 laser-initiated damage sites were micro-machined and other nearby damage sites were left un-touched. The laser beam simultaneously illuminated both the mitigated and un-mitigated sites during the test, so that the sites could be compared for changes.

The test procedure was to illuminate the sample with laser pulses in the range of 8 J/cm<sup>2</sup> to 10 J/cm<sup>2</sup> for 5 to 10 shots at each fluence. Schlieren images were taken and examined after each laser shot to determine if any changes occurred to the tested sites.

#### 3.2 Estimation of frictional heating during micro-machining

The heating estimate has two parts. First, an estimate of the typical cut depth is made to obtain an estimate of the surface area of the dimple. Secondly, an estimate of the power dissipation accompanying cutting is made from the known bit size and the angular velocity. Combining these two quantities yields an equivalent heat source. Finally, assuming the heat penetrates a thermal diffusion length into the crystal, an estimate is made of the maximum temperature reached.

The single-crystal diamond tool (see Fig. 2) has a conical radius of 0.05mm. The tool is applied at about a 45° angle to the surface. The tool produces a dimple with a shape as shown in Fig. 4 and the size depends on the depth of penetration. For the purpose of this calculation we use a “typical” cut depth of 20 μm, giving an area estimate of ~9x10<sup>-4</sup> cm<sup>2</sup>. To estimate the force due to drilling we use a coefficient of kinetic friction of 0.4 that is appropriate for glass on glass. The frictional force depends on the force normal to the surface, which is unknown. If we assume a range of values from 10<sup>-1</sup> to 10<sup>-2</sup>N for the normal force, then the friction force range is:  $F_f = 4 \times 10^{-3}$  to  $4 \times 10^{-2}$  N. The tool rotates at 65,000 rpm so the velocity is  $v = 5.1 \times 10^{-4} \text{ m} \times 1083/\text{sec} = 0.55 \text{ m/sec}$ . Thus power is dissipated at the rate:  $P = F_f v = 2.2$  to  $22$  mW. This power is dissipated over the area of the cut,  $A \approx 9 \times 10^{-4} \text{ cm}^2$ , so the input heat is:  $Q = P/A \approx 2.5$  to  $25 \text{ W/cm}^2$ . After a time  $t$ , this heat will be spread over a distance equal to the thermal diffusion length. Thus the temperature rise  $T$  will be of order:  $T(t) = \sqrt{4Dt} \cdot Q/k \approx 50$  to  $500 \cdot \sqrt{t}$  (K) where  $D$  is the diffusivity and  $k$  is the thermal conductivity. This temperature range includes melting and dissociation temperatures for KDP and DKDP crystals, respectively. The effect of locally high temperature is uncertain, however it may help to produce a smooth dimple that is benign to further damage.

### 4. RESULTS

The results of the tests of the micro-machined dimples on un-damaged crystals are given in Table 1 and the results for mitigated sites are given in Table 2. The dimples on both un-damaged surfaces of an AR coated KDP crystal are stable (ie., show no changes) for 526nm, ~3.2ns pulses at fluences from 8-12J/cm<sup>2</sup>. Other tests confirmed that the dimples on both surfaces of an AR coated DKDP crystal are stable, for 351nm, ~3ns pulses at fluences from 8-10J/cm<sup>2</sup>. Two out of 28 dimples that were machined on un-coated DKDP showed some change during a 400 shot sequence. One of the 24 mitigated damage sites damaged during testing at 9J/cm<sup>2</sup> fluence, possibly due to inadequate removal of the damage-affected material. Fig. 5 shows that micro-machined dimples are stable upon exposure to many shots, while other nearby surface damage grows. An example of the successful mitigation of an existing surface damage on a DKDP sample is shown in Fig. 6.

Table 1. Results of laser experiments to test the stability of micro-machine dimples on un-damaged crystal surfaces.

| Material | $\lambda(\text{nm})$ | Fluence( $\text{J}/\text{cm}^2$ ) | Pulse length(ns) | # Shots | #Sites | #Sites changed |
|----------|----------------------|-----------------------------------|------------------|---------|--------|----------------|
| KDP      | 527                  | 14                                | 3                | 10      | 24     | 0 (AR coated)  |
| DKDP     | 351                  | 14                                | 11               | >400    | 26     | 2 (un-coated)  |
| DKDP     | 351                  | 8 - 10                            | 3                | 10      | 35     | 0 (AR coated)  |

Table 2. Results of laser experiments to test the stability of micro-machine dimples after removing surface damage.

| Material | $\lambda(\text{nm})$ | Fluence( $\text{J}/\text{cm}^2$ ) | Pulse length(ns) | # Shots | #Sites | #Sites changed |
|----------|----------------------|-----------------------------------|------------------|---------|--------|----------------|
| DKDP     | 351                  | 14                                | 11               | >400    | 2      | 0 (un-coated)  |
| DKDP     | 351                  | 8 - 10                            | 3                | 5 - 8   | 24     | 1 (AR coated)  |

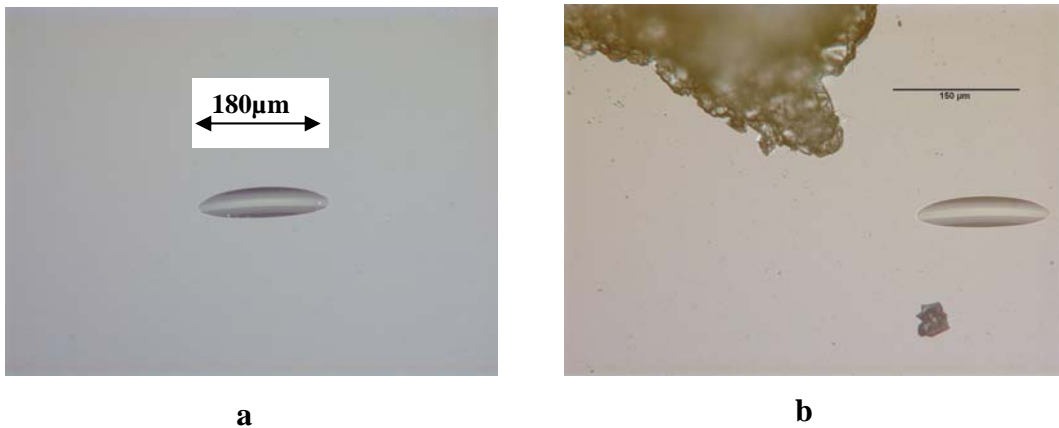


Figure 5. A demonstration of the stability of a micro-machined dimple on a crystal surface, under laser test conditions at 351nm. a) is an image of an isolated dimple on an un-damaged crystal surface. b) is an image of the same dimple after 600 laser shots at 12J/cm<sup>2</sup>, showing that it is un-changed while nearby surface damage grows.

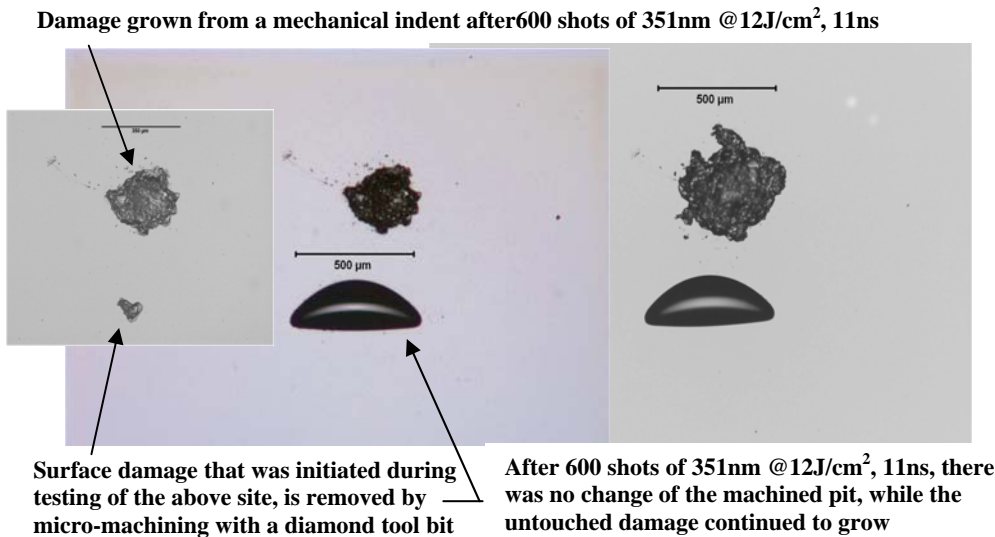


Figure 6. An example of the successful mitigation of a growing, laser-initiated surface damage on DKDP.

## 5. CONCLUSIONS

This work shows that spot micro-machining, using a high-speed drill with a single-crystal diamond bit, successfully removes surface damage and prevents its growth for 96% of the tested sites on small-scale crystal optics. Manual control of the process has been successfully demonstrated and automatic control should be feasible. The process that is demonstrated here is scalable and it could be applied to mitigate surface damage growth on large-scale KDP/DKDP optics.

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